Creare

Engineering Research and Development

July 6, 2004

U.S. Army TACOM-ARDEC
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Dear Mr. White:

Enclosed please find the final technical report for Creare project number 7404, "Real-Time Robotic Control System for Titanium Gas Metal Arc Welding." This report is submitted in satisfaction of the requirements of the Contract W15QKN-04-C-1042, CDRL A002. It covers the period from January 13, 2004 through July 12, 2004. Our contract states that you will review and provide comments within 14 days of receipt, after which time we will revise the report and resubmit it to you within 10 days of receipt of your comments.

Please call me if you have any questions.

Sincerely,

Robert Kline-Schoder
Project Director

7404/lam

Enclosure: Creare TM-2360
Form DD250
SF 298

cc: Contract File
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Final Report

REAL-TIME ROBOTIC CONTROL SYSTEM FOR TITANIUM GAS METAL ARC WELDING

TM-2360 July 2004

REAL-TIME ROBOTIC CONTROL SYSTEM FOR TITANIUM GAS METAL ARC WELDING

Final Report
January 13, 2004–July 12, 2004
Unclassified
CDRL Data Item No. A002

A Phase I SBIR Project for U.S. ARMY TACOM-ARDEC

Contract No. W15QKN-04-C-1042
Creare Project 7404

Robert Kline-Schoder—Project Director
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TABLE OF CONTENTS

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13. ABSTRACT (Maximum 200 words)

Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of future lightweight systems. There are initiatives to develop low-cost titanium materials supplies; however, low-cost and high-rate fabrication processes are sorely lacking.

Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of joining parts. Improved welding technology increases product lifetimes and makes possible the fabrication of large structures. Gas Metal Arc Welding (GMAW) has the potential to significantly improve the quality, speed, and penetration depth of titanium welds, while reducing the cost per part. However, this result can only be achieved if proper weld parameters are selected and dynamically maintained during the welding process due to the nature of titanium.

During this Phase I SBIR project, we have successfully demonstrated the feasibility of our innovation by determining the requirements for the system for both Army and commercial applications; designing, fabricating, and testing one of the key sensors used in the adaptive control system; determining the hardware necessary to adequately measure the weld temperature for control use; and designing a prototype control system for Ti GMAWto be fabricated and tested during the Phase II project.

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1 INTRODUCTION

This is the final technical report for a Phase I SBIR project that is being performed by Creare Inc. for the U.S. Army TACOM-ARDEC. It covers the time period between January 13, 2004 and July 12, 2004. The specific aim of this project is to develop a Real-Time Robotic Control System for Titanium (Ti) Gas Metal Arc Welding (GMAW) for current and future Army and commercial applications. GMAW is a particularly attractive welding process for Ti because of its potential for high deposition rate, deep penetration, and low cost. We will achieve our objective by developing an integrated system that will measure characteristics of the weld, the arc, and the metal transfer mechanism and use these data to adjust the weld current, voltage, and speed. Our system will make use of both existing weld hardware, new instrumentation, and computational algorithms to enable a significant improvement in the ability to weld Ti.

2 SUMMARY

The Need. Joint Vision 2020 advocates for the development of flexible, effective, and efficient multi-dimensional forces capable of rapidly projecting overwhelming military combat power anywhere in the world. To support this vision, the Army is developing the Future Combat Ammunition Suite and Structures (FCS), Objective Individual Combat Weapon (OICW), and Objective Crew Served Weapon (OCSW) programs. As part of this vision, the largest FCS vehicles must be lighter than current mechanized systems with each system possessing common or multi-functional characteristics and capabilities. Thus, weight reduction is of primary importance for FCS, OICW, and OCSW to meet their operational objectives. Low-cost sources of titanium (Ti) are becoming available and, as a result, it is being employed in these and other systems to reduce weight significantly and enhance corrosion resistance. However, low-cost manufacturing technologies for Ti have not kept pace with the demand for high production rate and low cost. Most Ti alloys can be welded with typical arc welding processes. However, to consistently achieve high weld quality requires a proper gas mixture/shield, adjustment of the weld parameters, and guidance for the weld arc that can wander substantially during the welding of titanium. Without substantial improvements to a viable high-rate welding process, the benefits of titanium structures, components, and weapons will not be realized.

Creare's Innovation. The objective of this project is to develop a Real-Time Robotic Control System for Titanium Gas Metal Arc Welding (GMAW) (also known as Metal Inert Gas, or MIG Welding), for current and future Army and commercial applications. Pulsed GMAW, in particular, is an attractive welding process for Ti because of its potential for high deposition rate, deep penetration, and better control of droplet formation, transfer, and deposition resulting in low fabrication cost. Pulsed GMAW welding of titanium is not currently a standard practice, but has been shown to have great promise by the Army. For example, ARDEC has successfully fabricated titanium prototype receivers in support of the M240 Machine Gun Lightweight Initiative, the upper hull for a Composite Armored Vehicle (CAV) Integrated Hybrid Structure (IHS), and an all titanium mortar baseplate for the U.S. Marine Corps using robotic pulsed GMAW; however, before the process can be considered for production, real-time control of the process is mandatory.

We will achieve our objective by developing an integrated system that will continuously measure characteristics of the weld, the arc, and the metal transfer mechanism and use these data to adjust the weld current, voltage, speed, and arc concentration. Our system, shown schematically in Figure 1, will make use of both existing robotic weld hardware and new instrumentation and computational algorithms to enable a significant improvement in the ability to weld Ti. The Creare real-time weld control system will integrate: (1) feedback sensors such as weld width, weld temperature, droplet formation, detachment, and transfer; (2) adjustment of weld parameters such as current, arc length, and torch speed; and (3) real-time adaptive control algorithms that are used to make critical changes to the weld parameters during welding to achieve high-quality welds.

Phase I Results Prove Feasibility. During Phase I of this SBIR development project, Creare has clearly demonstrated the utility of our innovative Real-Time Robotic Control System for Titanium GMAW. During the Phase I effort, we: (1) determined the requirements for the system to be of use to both Army and commercial applications; (2) designed and fabricated a prototype of one of the sensors that will be used in the adaptive control system; (3) used the prototype sensor to measure the droplet formation and transfer during pulsed GMAW of steel and titanium; (4) determined the hardware necessary to adequately measure the weld temperature for control use; and (5) designed a prototype control system for Ti GMAW that can be fabricated and tested during the Phase II project. These results exceeded our proposed Phase I technical objectives and clearly show the feasibility of our concept. Furthermore, a separate Creare development related to the guidance of metal cutting arcs is directly applicable to a guided pulsed GMAW process and will be funded separately in parallel with the Phase II effort with non-SBIR funds. During the Phase II effort, we expect to achieve all of the specifications to meet the Phase III applications by optimizing the hardware design, implementing the optimized hardware design, performing open loop tests to verify accuracy and dynamic range of the sensors, and demonstrating the use of our Real-Time Robotic Control System for Titanium GMAW using a pulsed power supply to control droplet formation on applications of interest at ARDEC.

The Benefits. The primary benefits of Creare's Real-Time Robotic Control System for Titanium Gas Metal Arc Welding include: (1) high quality titanium welds for use in critical fabrication and manufacturing processes; (2) high-speed welding that will reduce recurring manufacturing costs for lightweight structures; and (3) lower fixed costs because of the minimal capital equipment investment required for GMAW systems. This combination of benefits will enable the fabrication of very lightweight, very capable systems for use in FCS, OICW, and OCSW. Commercial applications are equally numerous in the aerospace, automotive, and construction industries. Our system for pulsed GMAW welding of titanium is an enabling technology that could substantially expand the demand for titanium leading to the proliferation of titanium welded structures, which will correspond with the advent of lower cost titanium.

Creare Is Extremely Well Qualified. Creare is highly qualified to develop and commercialize the proposed Real-Time Robotic Control System for Titanium Gas Metal Arc Welding. The proposed program builds upon and expands our base of successful technology innovations in the areas of titanium welding, laser-guided plasma cutting, robotics, feedback control systems, and manufacturing and materials process development. Creare personnel have

experience in all of the requisite technologies including: Ti welding; weld quality monitoring; lasers; real-time control systems; instrumentation development; signal and image processing; and robotic manufacturing systems.

Commercial Potential. Our Real-Time Robotic Control System for Titanium Gas Metal Arc Welding has tremendous commercial potential. While the cost of titanium is dropping and new low-cost production processes are poised to drop the price further, there is no viable high-rate joining process that will enable the cost-effective fabrication of titanium structures. Our system will fill that void allowing titanium to reach its marketplace potential. As such, the proposed work is critical and has substantial commercial upside.

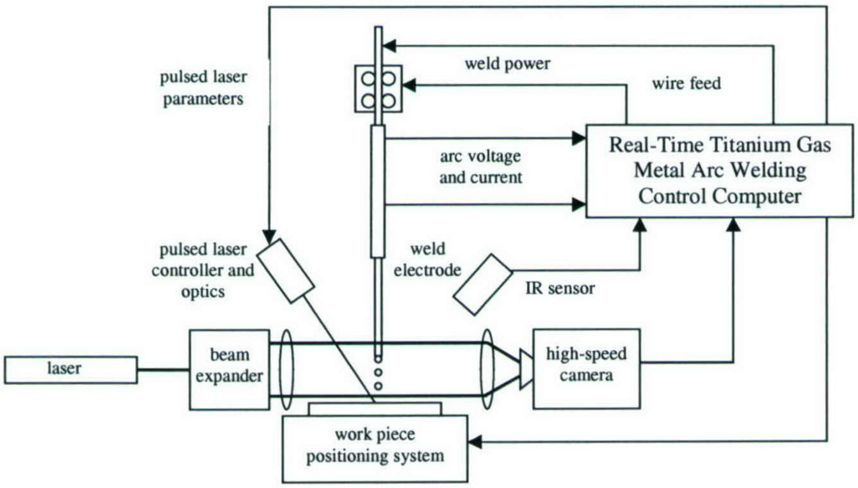

Figure 1. Conceptual Implementation of Creare's Real-Time Robotic Control System for Titanium Gas Metal Arc Welding. Our robotic GMAW control system uses advanced instrumentation sensors (laser backlight system for monitoring droplet characteristics and infrared temperature sensor for monitoring weld characteristics) to implement a real-time, adaptive control system. We will use these sensor measurements to determine optimized welding parameters. The development of an advanced pulsed laser to guide the arc size so arc placement is predictable and repeatable is to be funded under a separate non-SBIR effort along with its integration with the control system.

3 SIGNIFICANCE OF THE PROBLEM

Future Army Forces Need To Be Lightweight. A recent Defense Planning Guidance document states that the Army needs to develop an Objective Force that is capable of operational maneuvers from strategic distances; can penetrate and sustain operations in environments where access is denied; and be less dependent on traditional air and sea ports of entry and host nation support, reception, and infrastructure. The Army's responsibility to satisfy this requirement demands the development of a future full spectrum force that will be organized, manned, equipped, and trained to be strategically responsive, deployable, agile, versatile, lethal, survivable, and sustainable across the entire spectrum of military operations.

Titanium Is an Important Enabling Structural Material. Titanium and its alloys have proven to be technically superior and cost-effective materials for a wide variety of aerospace, industrial, marine, and commercial applications. Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of lightweight systems. The use of titanium has the potential to achieve significant reductions in the mass of systems as compared to steel analogs. For example, the XM777 Lightweight Howitzer weight was reduced from 17,000 lbs to 9,000 lbs with a design that was based on using titanium structural components for approximately 80% of the vehicle. Furthermore, low-cost sources of bulk titanium are being developed to supply the material needed to employ Ti in future Army and commercial structures.

Welding Is a Critical Manufacturing Process. The need for higher quality, less expensive, and more robust products has helped to spur the development of welding processes. All manufactured products have joints that join different pieces of metal together. More often than not, the joints are the weakest part of the structure and the joint quality determines the quality of the end product. Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of fabricating quality joints. Improvements in welding have resulted in increased product lifetimes and enabled the fabrication of large structures.

Titanium Welding Is Particularly Difficult and Expensive. One of the factors limiting the use of titanium in military systems is the lack of an acceptable Gas Metal Arc Welding, GMAW (or MIG) welding process approved for military fabrications. Almost all titanium is welded using a laborious and time-consuming Gas Tungsten Arc Welding, GTAW (or TIG) process. In comparison, both steel and aluminum are capable of employing GMAW systems with significant productivity improvements of ten times the GTAW systems.

GMAW systems have not been employed successfully in titanium due to several constraints, which mostly contribute to interstitial contamination. Interstitial increases of O>500 ppm, N>50 ppm and H>35 ppm are typical with GMAW systems currently available from equipment dealers. A large portion of this contamination is derived from the typical spatter generated during the process. This spatter or spitting of molten titanium to the outside of the protective gas coverage envelope leads to a potential re-ingestion of the contaminated material. Also, the turbulence of the protective gas stream from a turbulent arc leads to gas contamination. Some investigators have attempted to solve, with questionable success, these problems with extensive leading and trailing shields, which limit visibility and mobility of the weld torch, and thus limit the ability to weld structures of significance.

The factors controlling the spattering or spitting are well understood and have been largely addressed in the latest Gas Metal Arc Welding-Pulsed (pulsed GMAW) equipment produced from Lincoln Electric in their Power Wave 455 with computer wave control. This system, under the Army Titanium Manufacturing Technology Objective (MTO), has shown to have a dramatic reduction in sputtering by incorporating a high-pulsed rate waveform, which also incorporated a pre-heat in each pulse. This micro-adjustment in wave shape or form is possible because the system is capable of being programmed (controlled) by a separate stand-alone computer.

Under the Titanium MTO, ARDEC is demonstrating the pulsed GMAW process on several applications of importance. One such example is the fabrication via pulsed GMAW process of an all titanium mortar baseplate for the U.S. Marine Corps (weight reduction from 135 lbs to 65 lbs). The baseplate demonstration illustrates the promise of pulsed GMAW. However, fabrication using pulsed GMAW still takes considerable operator intervention to adjust weld parameters due to the nature of titanium and arc interactions. Thus, before the process can be transitioned to the Army's production base, reliable real-time robotic control is needed to adjust the weld parameters dynamically during the fabrication process based on measured weld quantities.

4 PHASE I PROJECT RESULTS

The specific objective of the Phase I project was to develop and demonstrate prototype instrumentation hardware for enhancing the quality and speed of performing titanium gas metal arc welding. During Phase II, we will combine the instrumentation, adaptive control algorithms, and real-time hardware in a complete control system for pulsed titanium GMAW. The specific questions posed in the Phase I proposal and the answers that we found during Phase I include:

- Can laser backlighting instrumentation be developed to measure and monitor GMAW drop formation and transfer? **Yes.** We fabricated a prototype sensor and obtained images from the system in real time using a pulsed GMAW system on titanium and have designed an instrument for use during Phase II.

- Can an infrared detector be used to monitor the weld pool temperature during GMAW of titanium? **Yes.** Based on a literature survey, we located an infrared temperature detector that can be used to measure the weld temperature in situ. This instrument will be the basis for the Phase II design for measuring the weld temperature.

- Can the necessary real-time control algorithm processing and instrumentation hardware for enhanced titanium gas metal arc welding be implemented in real time and in a package compatible with Army manufacturing facilities? **Yes.** The control algorithm we have designed can be implemented in real time with current-generation computers. The most computationally intensive portion of the algorithm will be interfacing the measurement instruments to the computer and extracting the required information. This will require the development of image processing routines to extract the droplet information from the laser backlighting system.

In addition to answering these questions, under separate funding we developed the concept and demonstrated the ability to control a plasma using a low-power pulsed laser. This innovation was developed for a separate purpose, but has wide ranging application to Ti pulsed GMAW. As a result of this additional innovation, we have been able to secure funding from the Army Titanium MTO focused on developing manufacturing processes for titanium and integrating the process with the real-time control system that we will develop under the Phase II SBIR.

Creare's solution, shown schematically in Figure 1, is based on combining state-of-the-art sensor instrumentation, adaptive control algorithms, pulsed laser plasma

concentration, and real-time hardware to measure and monitor the weld characteristics and modify the weld parameters in real time. Our Real-Time Robotic Control System for Titanium GMAW will consist of sensors for measuring characteristics of the weld, the arc, and the droplet formation and transfer and use these data to adjust the weld current, voltage, and speed. We expect that by combining these components into a complete robotic welding system that we will achieve higher quality, lower cost, and more robust titanium welds than are currently possible today. Below is a description of the sensors, control algorithm, and real-time hardware that we expect to employ in our system.

4.1 SENSOR INSTRUMENTATION

The sensors make up some of the most important components of the robotic titanium weld control system. The sensors are used to observe and measure characteristics of the weld. These measurements then serve as the signal that is used to adjust the welding parameters. Several measurement techniques have been developed in order to measure the penetration depth (e.g., ultrasonic sensors, X rays, weld pool oscillations, optical devices, acoustic emissions, and infrared sensors) and the droplet formation and transfer. We will employ a laser backlight system for monitoring the droplet formation and transfer mechanism and infrared sensing to monitor aspects of the weld formation. Below is a description of each of these sensors, how they will be applied to the monitoring of important weld characteristics, and important Phase I findings related to the particular sensor.

Laser Backlight Arc Sensor. As part of past research, the Principal Investigator developed a laser backlighting system to monitor the droplet formation and transfer in a gas metal arc welding system. Laser backlight sensors for GMAW have heretofore been special-built laboratory devices, not commercially available. During the Phase I project, we fabricated a prototype of a laser backlight sensor that can be made commercially available and demonstrated its performance during welding of steel and titanium. The backlight system, shown schematically in Figure 2, shows that an expanded laser shines through the arc and is projected onto a high-speed video camera. The laser light is of sufficient intensity and pointed in the direction of the video camera such that the weld electrode appears as a shadow in the image on the camera. When drops form and detach, they too appear as a shadow in the camera image and if the camera is fast enough, it is quite easy to watch the formation, detachment, and transfer of the drop from the electrode to the work piece.

The mechanism of drop formation and detachment depends on the forces acting on the droplet. According to a static force balance, the forces acting to detach the drop include gravity, electromagnetic, and the plasma drag force. The main force retarding detachment is surface tension. When the forces acting to detach the drop exceed the forces retarding detachment, the drop detaches. During its growth, the droplet oscillates vertically at the tip of the electrode. If the electromagnetic forces can be timed properly, the oscillation can be used to facilitate the droplet detachment and subsequent transfer.

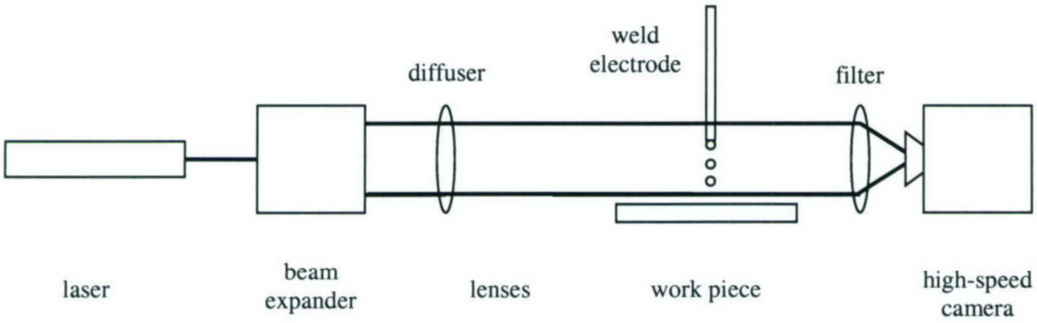

Figure 2. Block Diagram of Laser Backlight Sensor. This sensor can be used to monitor the droplet formation, detachment, and transfer from the electrode to the work piece. The expanded laser shines through the weld arc. Since the laser light is directional and points directly into the video camera, the electrode and droplet appear as a shadow in the image. By processing this image, we can determine important characteristics of the weld.

An example of the images captured using the laser backlight system during the Phase I project are shown in Figure 3. The hardware used to obtain these images is shown in Figure 4. The picture on the left shows that the laser, beam expander, and diffuser in the foreground. The filter and high-speed camera are in the background partially hidden by the weld head. The work piece is attached to a Bug-O positioning system which translates the work piece during welding. The pulsed welding power supply is shown in the picture on the right. The power supply to the weld head was pulsed approximately 80 times per second for the tests that we performed. In particular, we used a pulsed GMAW system from Lincoln Electric. The particular waveform that was used to drive the transfer is shown in Figure 5.

The images shown in Figure 3 were obtained with the high-speed video camera running at 1000 frames per second during welding of titanium. The image in Frame 1 clearly shows the formation of the drop. The weld current and voltage are pulsed in Frame 2 according to the sequence in Figure 5, which causes the drop to be squeezed and ejected from the wire. Then, the drop is transferred to the work piece. This sequence of images clearly demonstrates the feasibility of measuring these important parameters using our sensor and the advantages of using pulsed GMAW for Ti. With this information, we will be able to characterize the welding process and use this information to adjust the weld parameters, including the arc current waveform, which is the central thesis of this project.

During Phase II, we will develop a compact laser backlight system so that it can be easily integrated into the weld head hardware and perform image processing to automatically determine that the drop is forming at the end of the electrode and to identify the transfer mechanism. The drop can transfer under a small number of distinct ways: short-circuiting, globular, projected spray, streaming, and rotation. It is desirable to achieve a spray transfer with one drop per pulse because of the large range of possible adjustments in the welding parameters. These different mechanisms arise as the weld current is increased. This measurement will then be available in real time for use in our weld parameter adjustment system.

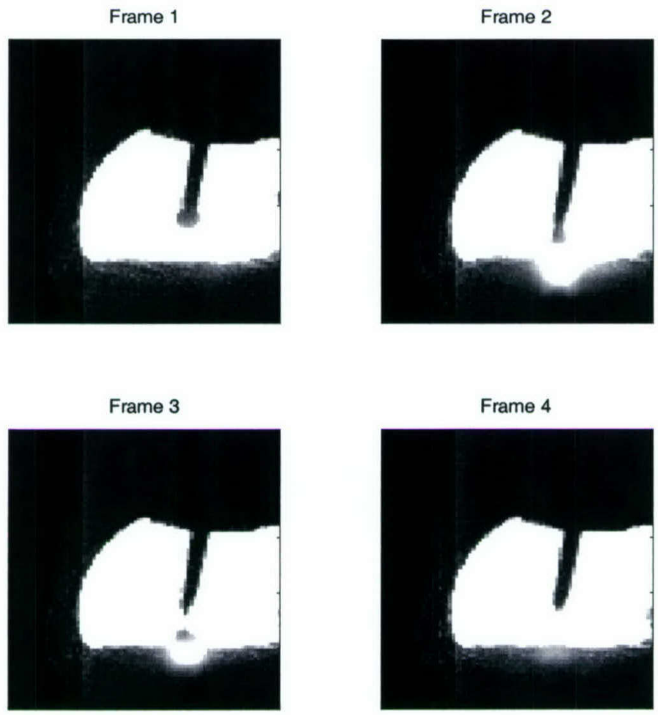

Figure 3. Real-Time Images from Laser Backlight Sensor Prototype. The images shown in this sequence were obtained from our laser backlight sensor prototype during gas metal arc welding of titanium. The images clearly show the formation of the droplet and the transfer of the droplet from the weld wire to the work piece. Images such as these can be used to determine the welding mode and the speed of droplet transfer, both important pieces of information when setting the weld parameters.

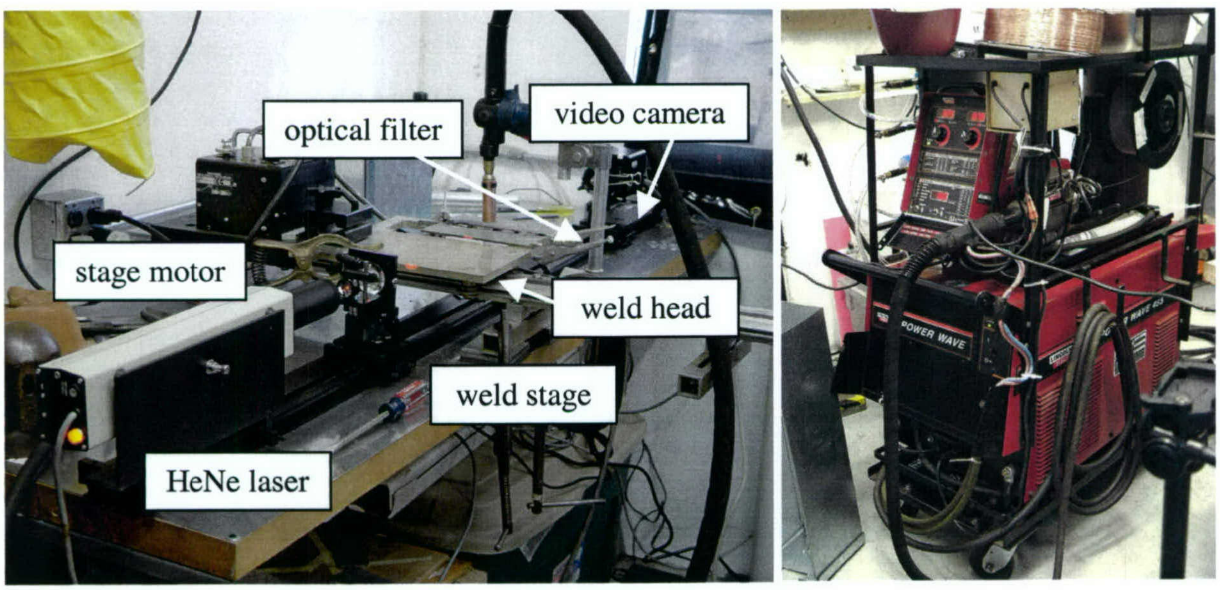

Figure 4. Photo of Welding Setup. The primary components (the laser backlight imaging system, titanium welder head, and Bug-O track to hold test piece) are shown on the left. The pulsed GMAW power supply is shown on the right.

Figure 5. Waveform Used to Effect Proper Transfer During the Pulsed GMAW Tests During Phase I. This pulse form is an optimized sequence for titanium. This waveform cannot currently be varied in response to weld conditions. In Phase II, we will dynamically change the waveform to control the weld process.

Infrared Temperature Sensor. Infrared sensing has been used to monitor various aspects of the welding process for many years. Infrared cameras, thermocouples, and various combinations of these devices have been used to measure the temperature distribution around the weld pool in order to automatically track seams, control the bead width, or regulate the weld penetration. The temperature distribution near the weld pool provides important information on the status of the welding process. The weld parameters (voltage, current, and speed) and other process variables (joint mismatch, root gap, thickness of parts, and part composition) effect the pool shape (determined from temperature distribution), the absolute temperature near the pool, and the temperature distribution symmetry around the pool. Thus, by measuring the temperature distribution, many of the weld parameters and variables can be determined indirectly from the temperature.

All materials emit infrared radiation which is related to their temperature (i.e., thermal energy). The infrared spectrum encompasses electromagnetic wavelengths from 0.7 to 1000 microns and the intensity of radiation emitted by an object is a function of the temperature of the body and the surface emissivity (a material dependent property). If the emissivity of the material is known and the infrared radiation of the object is measured, the temperature can be determined using the Stefan-Boltzman formula.

The use of infrared sensors makes monitoring the temperature very convenient. Infrared sensors are inexpensive and the fact that they do not require contact between the sensor and the

object (which is at high temperature), makes them easy to use for monitoring temperatures during welding. The sensors can be used on moving targets, in a vacuum, and in hostile or inaccessible regions. The sensors themselves have fast response and are easy to adapt to the floor of a shop or fabrication facility. The sensors convert the infrared radiant energy into electrical energy which can be used to monitor the temperature and extrapolate other important weld quantities.

We plan to make use of a pyrometer. A pyrometer is a simple instrument that measures temperature by directly sensing the amount of thermal radiation from an object. In this design, a lens will focus the radiation onto an optical fiber which will transfer the infrared energy to an infrared detector that can be located remotely from the harsh welding environment. The signal from the infrared detector is then provided to the control computer so that it can process the raw data from the sensor and use that data in the weld parameter control algorithm. The pyrometer will be configured to receive radiation from a fixed circular spot size on the order of 4 inches (10 cm) in diameter. This will measure the average temperature across the weld, rather than attempting to measure the temperature profile. Based on our past experience and the experience of others reported in the open literature, we believe that the additional profile information would not be worth the complexity and expense that would be required to measure the weld temperature profile.

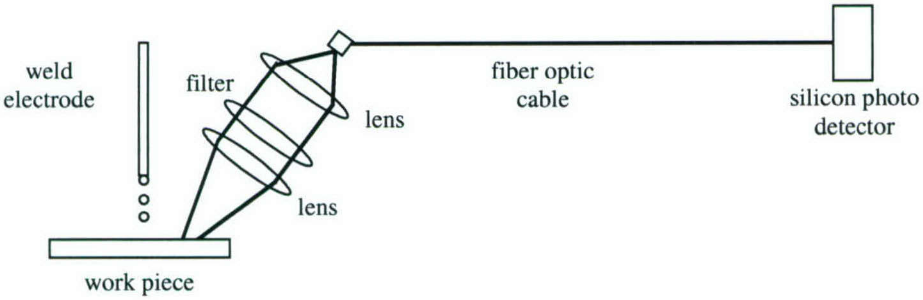

Figure 6. Block Diagram of Infrared Temperature Sensor. This sensor can be used to monitor the temperature of the weld pool. The infrared image is focused on the end of the fiber optic which transfers the image to the silicon photo detector. The photo detector is connected to the control computer which digitizes and processes the raw data to obtain the temperature.

4.2 CONTROL ALGORITHM

Background. As described above, an optimum gas metal arc weld will result from a projected spray droplet. Also, since the electromagnetic forces on the droplet can be controlled by controlling the welding power supply current and voltage, much past research in the control of GMAW employs electrical control to regulate the droplet behavior. We, too, will follow this approach because it is a reliable and fast method of affecting the droplet formation and transfer. In this approach, the droplet detachment and transfer is controlled by adjusting dynamic parameters of the weld, such as the background current and period and a superimposed (or pulsed) current and its period. By appropriately setting the welding current and waveform, we expect to be able to achieve a one drop per pulse transfer where the drop is the same diameter as the electrode wire, the detachment occurs when the current is pulsed, and the arc guides the drop to the proper location in the weld.

In order to implement this control algorithm, the welding power supply will be a current-controlled unit that has good voltage and current properties. In the one drop per pulse mode, the droplet is formed when the current is pulsed and the background current is used to prevent the arc from extinguishing. In this mode, the melt rate of the wire is proportional to the pulse frequency, period, and level. The higher the frequency, the higher the average welding current and melting rate will be. Thus, the mass and heat transferred into the work piece can be controlled by regulating the background and pulsed welding current. As shown in Figure 5, the pulse is complicated for titanium GMAW. The first part of the pulse melts the end of the wire to form an attached droplet. Then the second multi-mode pulse first stretches the drop and then pinches it off to form the droplet that is transferred.

When the droplet has formed and is still attached, all of the weld current passes through the droplet. If the pulse current is held constant during this time, the droplet may overheat. If this happens, metallic vapor from the droplet will be generated and spatter may occur on the work piece. This results in the potential for significant loss of alloying elements in the weld. Thus, it is important to ensure that in this mode of operation the system will allow the average welding current and heat input to the work piece to be controlled while guaranteeing that the one drop per pulse mode of droplet transfer is sustained. Further, with the arc guidance and concentration provided by the pulsed laser, we expect to be able to guide the path of the droplet during transfer to the proper location in the weld (again, this laser guidance of the arc will be developed under separate funding). By combining these two effects, we can both control the drop transfer mode as well as the location of the drop in the weld.

Adaptive Controller. The primary limitation in applying established control theory to develop welding process controllers is that accurate models of welding processes are difficult to derive. This situation arises because welding processes are difficult to model exactly with first principle, physics models and empirical data gathered in a production environment is too limited to use standard system identification techniques. Without an accurate process model, the performance of any closed-loop system is limited.

We plan to use an adaptive fuzzy logic model to combine uncertain first-principle physical models with empirical data and to use this model to generate control inputs for subsequent processing runs. The advantages of fuzzy logic models for this application are that they can model nonlinear processes, be based on linguistic descriptions of relationships from experts, and be made adaptive to respond to changing systems and empirical data. With a good model, control inputs can be derived, for example, with a gradient search algorithm to minimize an objective function based on the model outputs.

Fuzzy logic can be considered one class of neuro-computational method (another example being neural networks). Fuzzy logic models, like all modeling techniques, implement a correlation between inputs and outputs. The unique features of fuzzy logic models, however, are that they can approximate any continuous function, that the rules and membership functions used to implement the correlation between inputs and outputs are derived from qualitative statements, and that the rules and membership functions are relatively simple to implement. Crisp input data are converted to fuzzy data (input truth values) in a fuzzification process (using one set of membership functions). A rule base is then used to compute corresponding output truth values

for the fuzzy input data. The result of the output truth value computation is then used to invoke particular defuzzification options (using a second set of membership functions). The defuzzification process effectively transfers the output truth values into crisp output data. Properly chosen membership functions and rules will yield proper modeling results.

We plan to implement an adaptive fuzzy logic model using a gradient search optimization routine during Phase II as follows. Data are generated from physical-based models and empirical measurements. These data are used to train the fuzzy logic model by comparing the data from physical-based models and empirical measurements with the predicted output from the fuzzy logic model. As an example, a gradient search optimization routine can be used to determine an optimum set of parameters that govern the correlation between fuzzy logic model inputs and outputs. Specifically, the fuzzy logic model implements a correlation between input numbers (recipe settings) and output numbers (process characteristics) using a set of parameters (fuzzy logic model descriptors).

Once the input/output function is optimized (i.e., an optimal set of model parameters is determined), a similar procedure can be used to determine an optimal set of inputs to achieve a desired output. In this case, however, the model parameters are fixed and the system inputs are varied to achieve an optimized performance index. The performance index is redefined to represent desired system behavior and the derivative of the performance index is calculated relative to the inputs (control settings). An iteration over the space of inputs is used to optimize the new performance index.

4.3 Real-Time Hardware

The Creare Real-Time Robotic Control System for Titanium GMAW will be based on hybrid analog/digital control electronics. To achieve sufficient bandwidth, high precision control with algorithm flexibility, and power, a hybrid design is necessary. The analog electronics are used to implement the high bandwidth actuator power driver and the proper signal conditioning for the instrumentation sensors. A digital microprocessor will likely be used to implement the control algorithm for all of the controlled welding parameters. We expect to use a microcomputer because of the image processing that will be required to determine the droplet formation and detachment and the fact that a physics-based model will be required to infer important weld characteristics from the infrared sensor measurements. Creare has experience in designing custom hybrid electronics and implementing real-time control systems using microprocessors. A block diagram of the real-time electronics hardware is shown in Figure 7.

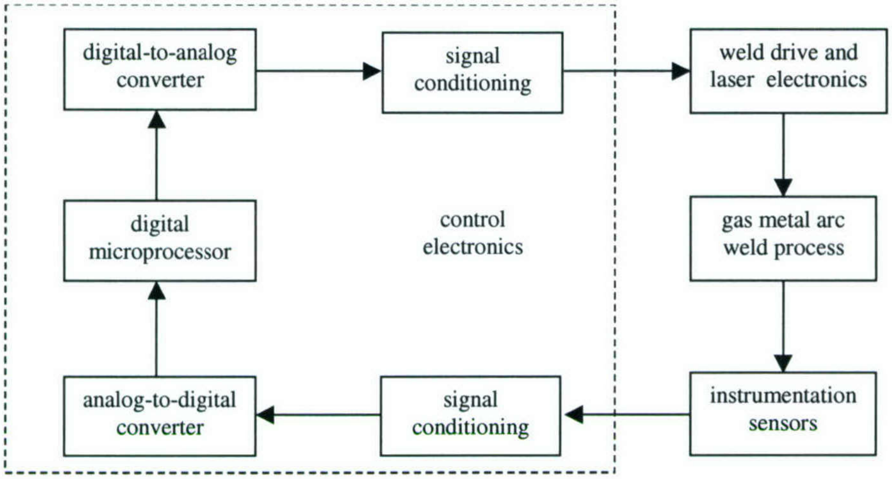

Figure 7. Block Diagram of Real-Time Electronics Hardware. This hardware is used to implement the adaptive control algorithm used to regulate the performance of the overall welding system.

5 CONCLUSIONS

Titanium addresses the Army's need for high strength-to-weight characteristics and can meet the performance and transportability requirements of future lightweight systems. There are initiatives to develop low-cost titanium materials supplies; however, low-cost and high-rate fabrication processes are sorely lacking.

Welding and joining technologies enable improved manufactured components by reducing the weight, production time, and cost of joining parts. Improved welding technology increases product lifetimes and makes possible the fabrication of large structures. Gas Metal Arc Welding (GMAW) has the potential to significantly improve the quality, speed, and penetration depth of titanium welds, while reducing the cost per part. However, this result can only be achieved if proper weld parameters are selected and dynamically maintained during the welding process due to the nature of titanium.

During this Phase I SBIR project, we have successfully demonstrated the feasibility of our innovation by determining the requirements for the system for both Army and commercial applications; designing, fabricating, and testing one of the key sensors used in the adaptive control system; determining the hardware necessary to adequately measure the weld temperature for control use; and designing a prototype control system for Ti GMAW to be fabricated and tested during the Phase II project.